Das Wetter. Berlin. 21 Jahrgang.

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—— Die Telegraphie ohne Draht und die Wetter-Vorhersage. Pp. 258–259.

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Beiblätter zu den Annalen der Physik. Leipzig. Band 28.

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Illustrirte Aeronautische Mitteilungen. Strassburg. 8 Jahrgang.

Elias, H. Die Geschwindigkeit von vertikalen Luftbewungen. Pp. 394–396.

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Physikalische Zeitschrift. Leipzig. 5 Jahrgang.

Conrad, V. and Topolansky, M. Elektrische Leitfähigkeit und Ozongehalt der Luft. Pp. 749–750.

Annalen der Hydrographie und Maritimen Meteorologie. Berlin. 32 Jahrgang.

—— Die Witterung zu Tsingatu im Juni, Juli und August 1904, nebst einer Zusammenstellung für den Sommer 1904. Pp. 525–529.

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Br. Ueber eine Ursache der Entstehung von Herbstnebeln. [Abstract of article of J. B. Cogen.] Pp. 539–540.

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Meteorologische Zeitschrift. Wien. Band 21.

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—— Langley über eine mögliche Aenderung der Sonnenstrahlung und deren wahrscheinlichen Effekt auf die Temperatur der Erde. Pp. 458–460.

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—— Zum Klima von Saigon. Pp. 483–484.

Memorie della Societa degli Spettroscopisti Italiani. Catania. Vol 33.

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AIRY'S THEORY OF THE RAINBOW.

By Rev. D. HAMMER, S. J., Canisius College, Buffalo, N. Y.

[Reprinted from Journal of the Franklin Institute, November, 1903.]

Up to some seventy years ago Descartes's view of the formation of the rainbow was universally accepted. In 1836 the English astronomer Airy published a new theory, but, as it often happens, it found few admirers, some admitting it only for the explanation of the so-called supernumerary bows. Of late years, however, several scholars have endeavored again to draw the attention of scientists to Airy's theory; as prominent among them may be mentioned Messrs. Mascart and Pernter.

Why, then, one might ask, is Airy's theory so little known while that of Descartes is almost universally taught? The reason may be found in the difficult calculations requisite for a full understanding of Airy's theory. If, therefore, the latter can not, to a sufficient degree at least, be brought within the reach of nonexperts in physics and higher mathematics, no one will require of our colleges and text-books to pay much attention to it. But this is not the case. In his "Ein Versuch, der richtigen Theorie des Regenbogens Eingang in die Mittelschulen zu verschaffen," Doctor Pernter succeeded in putting it into such form that it may without difficulty be introduced into high schools and colleges.

In this essay we shall strive for the same end; our material is drawn from Doctor Pernter's writings on this subject.[1]

In order to show the differences between the two theories, we first give a short account of that of Descartes.

Fig. 1 represents the formation of the principal rainbow. A bundle of parallel rays strikes the raindrop. The one that passes through the center of the sphere is not deviated from its course, but all the others undergo a change in their former direction, corresponding to the respective angles of incidence. Following up one of them we see that after two refractions and one reflection it makes a certain angle with the line *MN*, the axis of the rainbow. This angle we call *O*. If now we take different angles of incidence increasing at a constant rate from 1° to 90°, we find by construction as well as by calculation that the angle *O* varies unequally, growing larger and larger till, at an angle of incidence of about 59° 24′, having reached its maximum, it again retrogrades to 0. Near this limit *O* has its smallest rate of variation; hence, much more light will be accumulated on this spot than at any other place of the illuminated field. It is this crowding together of (say) red rays that enables us to see the red of the rainbow. Now, since every color has its own index of refraction, every color has also its own maximum *O*. From this consideration it naturally follows that we must always see the well-known seven colors of the rainbow, and that, provided the apparent diameter of the sun be the same, the width of the bow and its colors remain unchanged. The reason is, the index of refraction, on which the calculation depends, is a constant quantity, and the size of the raindrop, the only variable, is disregarded entirely. Hence, the characteristic mark of Descartes's theory is constancy. It is simple in itself and easily understood, but facts prove its insufficiency.

To convince the reader of this assertion, we are to give an accurate description of the rainbow, a task which, though at

[1] "Ein Versuch, der richtigen Theorie des Regenbogens Eingang in die Mittelschulen zu verschaffen," "Neues über den Regenbogen" and "Die Farben des Regenbogens."

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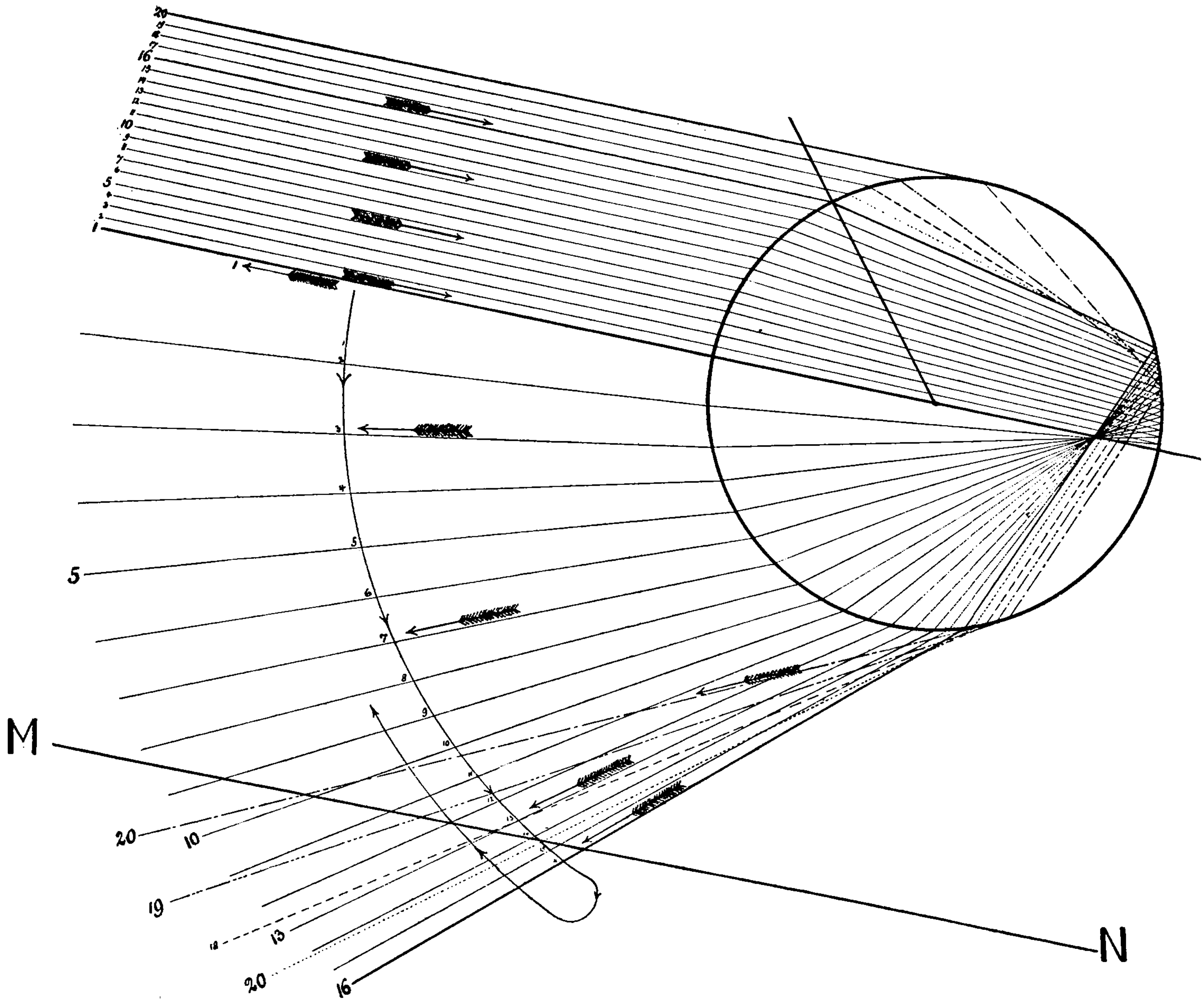

FIG. 1.—Illustrating Descartes's theory.

first sight may seem superfluous, is of real necessity, if we wish to correct several misconceptions. "Want of accuracy in observing the phenomenon," says Doctor Pernter, "contributed perhaps more than anything else to the fact that many were satisfied with an inadequate explanation, thus keeping up until the present day a properly false theory which otherwise would have been dropped."

Here we need not dwell upon such particulars as the axis of the rainbow, the concentricity of the arches, their division into principal and supernumerary bows (in the sequel we will designate the former as first, second, third, etc., rainbows; the so-called supernumerary bows we comprise under the name of "secondary" bows). All this supposed as known, we briefly enumerate those features which are sometimes overlooked, although just they furnish a strong proof that Descartes's theory is far from being complete enough to give a sufficient explanation of the phenomenon.

(1) In the principal rainbows the colors are neither always the same nor is their distribution constant. Most frequently no blue is seen, in other cases a really pure red is wanting; dark blue occurs rather as an exception. Now yellow almost disappears, whilst green and violet are prominent; again, yellow and green occupy the greater part, violet being reduced to a narrow extension. The intensity also changes; frequently the brightest spot lies in the beginning of violet. Finally, the variations in the width of both arch and its colors can not escape the eye of any attentive observer.

(2) The secondary bows are characteristic of the rainbows, so much so that they are by no means a rare occurrence and their absence is rather the exception. They often lie hard against the violet of the first rainbow and extend inward; under exceptionally favorable circumstances they border upon the violet of the second bow and extend outward. They, too, in accordance with the entire phenomenon, undergo several changes; their number varies from six to one, sometimes they are wanting altogether; mostly made up of green and rose, they now and then show yellow, green, and purple; or yellow, green, blue, and rose.

To the white rainbow we shall afterwards devote special attention on account of its importance for the new theory.

After this description of the rainbow, it is understood that that theory deserves our preference that accounts for all the numerous variations and explains the phenomenon in harmony with both light-theory and experiments. Airy's theory may justly claim this prerogative. According to it the rainbow is essentially a phenomenon of diffraction; this statement, as we are going to show, derives its proofs from theory as well as experiments.

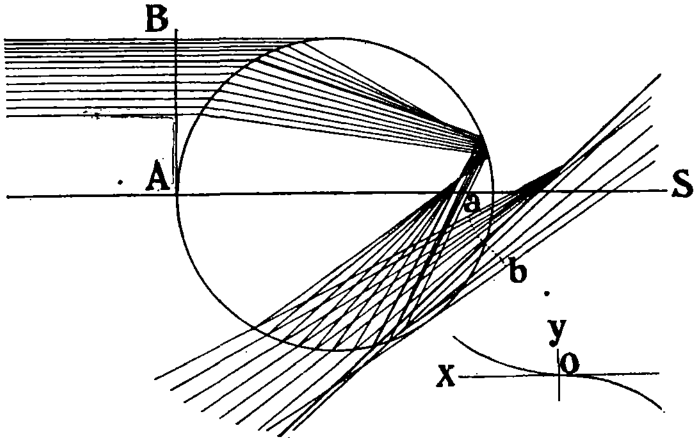

FIG. 2.—Illustrating Airy's theory. FIG. 2a.

Fig. 2 is constructed for rays whose index of refraction (n) equals $\frac{4}{3}$ (red-orange near the Frauenhofer's line C). As is seen, the rays which after refractions and reflection are prolonged backwards, form each a certain angle with AS, the ray that passes through the center of the sphere. This angle we call D. Its formula for all possible rainbows is:

$$D = k\pi + 2[i - (k+1)r],$$

k standing for the number of reflections, i for the angle of incidence, and r for that of refraction. Putting in p for $k+1$, we have

$$D = k\pi + 2\ (i - pr).$$

Examining the figure more closely we find that the heavy line occupies a peculiar position; for the angle it makes with AS is a minimum. This angle, which we may denote by Dm, is to be found by means of the formulas:

$$\sin I = \sqrt{\frac{p^2 - n^2}{p^2 - 1}} \text{ and } \cos I = \sqrt{\frac{n^2 - 1}{p^2 - 1}},$$

I standing for the angle of incidence corresponding to Dm.

In the subjoined table Dm is worked out for the five first rainbows:

For water.			For glass.		
k.	*I.*	*Dm.*	*k.*	*I.*	*Dm.*
	° ′	° ′		° ′	° ′
1	59 24	$\pi - 42$ 4	1	49 48	$\pi - 22$ 51
2	71 49	$\pi + 50$ 56	2	66 43	$\pi + 86$ 52
3	76 50	$2\pi - 42$ 48	3	73 13	$2\pi + 9$ 8
4	79 38	$2\pi + 43$ 46	4	76 48	$3\pi - 71$ 6
5	81 20	$3\pi - 51$ 42	5	79 6	$3\pi + 27$ 29

What then is the relation of the least-deviated ray to the formation of the rainbow? Fig. 2 shows it. All the rays, which come from a single point of the sun's surface and strike the drop, are practically parallel, owing to the great distance of the sun. Hence, the wave front can be designated by the line AB, perpendicular to one of them. But when the same rays leave the drop, their wave surface has necessarily become curved, as shown in the figure by ab. The curvature is such that the least-deviated ray forms its turning point. But somewhat divergent rays can not be united into one image in our eyes. Hence, in case the rainbow is perceived it can only be ascribed to rays that deviate least from parallelism. Such are those in the nearest vicinity of the least deviated ray. The very small portion of the wave, the rays of which are effective, is represented in fig. 2a, being, of course, highly magnified.

The mere shape of this wave front may tell us that we have to deal with the phenomenon of diffraction. This statement is based on Huyghen's principle, which says that the effect of a wave surface must be considered as the sum total of the effects of each point in the surface, whereby each point is taken as a wave former of its own, i. e., it sends out rays in all directions. In case of spherical wave fronts the final result is the same as if the wave had been produced only in the center of the sphere. But this is not true for other curved waves, particularly if there is a question of curvatures having a turning point. In this case diffraction must take place. If we use monochromatic light, an alternate series of light and dark bands will be observed; with white light these bands show a most beautiful variation of hues. Hence, the phenomenon is analogous to that observed through a diffraction grating. Still it offers a somewhat different character, since the producing wave surface is of a peculiar shape.

We now come to a point which Descartes's theory does not at all take into account, namely, the fact that the ever varying distribution of colors, and consequently the rainbow itself necessarily depend on the size of the drops.

The efficiency of the rays (fig. 2a) depends on the equation of the wave front. Calculation has established it to be

$$y = Hx^3,$$

wherein

$$H = \frac{h}{3a^2},$$

a standing for the radius of the drop and h for

$$\frac{(p^2-1)^2}{p^2\,(n^2-1)}\sqrt{\frac{p^2-n^2}{n^2-1}}.$$

From this equation it follows that such a wave surface necessarily gives rise to diffraction; moreover, since the radius of a drop enters as a factor into the equation, the further conclusion must be that with differently sized drops the phenomenon will show a different character. Given the equation and the radius of the drop we are enabled beforehand to construct the rainbow that will result. Professor Pernter undertook this weary task, and in an essay on the colors of the rainbow published the results obtained for drops whose radius respectively is 1000, 500, 250, 150, 100, 50, 40, 30, 25, 20, 15, 10, 5μ (μ = 1/1000 millimeter.)

The following four diagrams, fig. 3, we present to the reader, remarking that they are not the result of mere speculation, but that partly, at least, they were proved correct by actual experiments.

We must now prove that these theoretical conclusions have to do with the phenomenon of diffraction; the further conclusion is easily drawn that in case we use white light the different colors will overlap and thus give rise to mixed hues. Removing the glass and allowing the sunlight to fall upon the slit, a phenomenon is observed which is essentially the same as the rainbow seen in nature. For we observe a long series of bands: the first shows red on the one end followed by yellow, green, and violet (first bow), and the others (secondary bows) are a partial repetition of these hues.

We now proceed to the second part of the experiment. Instead of a cylinder measuring two to three millimeters in diameter, we use, say, one millimeter or a well-shaped glass thread. The contrast is striking. The bands are broader, the colors less saturated and partly of a different succession; the blue, which before could hardly be noticed, is now prominent. Hence, the phenomenon depends on the size of the cylinders. This conclusion, applied to the rainbow as it occurs in nature, gives a positive proof that the width of the entire bow, the width of the single colors, and their succession necessarily depend on the size of the raindrops. This we can understand better from figs. 4 and 5. They show how the intensities of the different colors are superposed. Fig. 5 especially gives us a fair idea of the final result, a white rainbow. (Cfr. No. I of fig. 3.) In the first set of intensities the maximum of all the colors occurs almost in the same spot; hence white is produced in the main part of the principal rainbow. Between the first and second set all the colors have their minimum intensity (=0) nearly at the same place, which explains the dark space between the principal and the first secondary bow as shown in No. I of fig. 3.

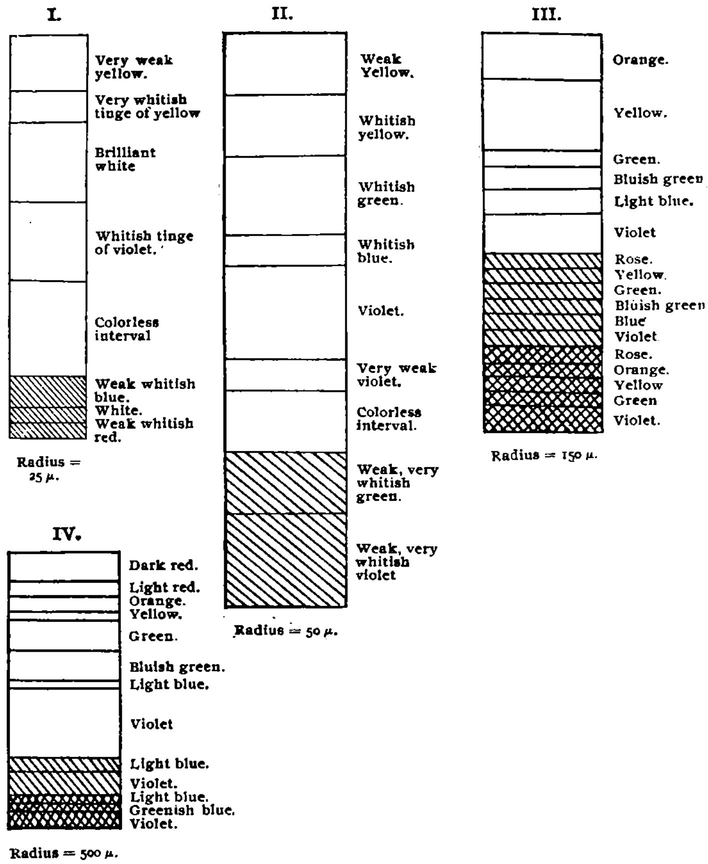

FIG. 3.—Four diagrams showing calculated rainbows. (Pernter.)

Calculations for $a = 500\,\mu$.			Experimental results for $a = 500\,\mu$.		
Angle.		x.	Angle.		Observed colors.
°	′		°	′	
42	10	Red..........	....		
42	0	Red..........	....		
41	50	Red.	....		
	40	Yellow	41	36	Maximum of intensity.
	30	Green..........	41	35	Limit between yellow and green.
	20	Green..........	....		
	10	Green..........	41	7	Limit between blue and violet.
	5	Blue	41	5	Beginning of the first violet.
41	0	Violet	....		
40	55	Violet	....		
	50	Violet	40	50	End of the first violet.*
	45	Blue	40	45	Beginning of the second violet.
	40	Violet	....		
	35	Violet	....		
	30	Rose	40	30	Middle of the second violet.
	25	Rose	40	25	End of the second violet.
	20	Blue	....		
	15	Bluish green ..	....		
	10	Blue	....		
	5	Rose	40	2	Middle of the third violet.
40	0	Rose	40	0	End of the third violet.
39	55	Blue	....		
	50	Bluish green..	....		
	45	Blue	....		
	40	Rose	....		
	35	Rose	39	38	Middle of the fourth violet.
	30	Blue	....		
	25	Blue..........	....		
	20	Violet	....		
	15	Roes	....		

*Average of three values.

Thus far the experiment affords a general proof for the correctness of Airy's theory; its performance requires neither a skillful experimentalist nor a well furnished laboratory. However, a strictly scientific confirmation of the theory should be derived from experiments carried out with cylinders or drops of water, since it is water which in nature gives rise to the rainbow. W. H. Miller was the first to make experiments in this line; afterwards they were taken up especially by Mr. Mascart, who in 1888 published his extensive and exact researches in the Comptes Rendus. But since in the latter experiments only monochromatic light was made use of, Doctor Pernter saw himself necessitated to employ white light in order to have his calculations corroborated by experiment. Since their results demonstrate the accuracy of Airy's theory we think it proper to present them in their essential features.

A cylindrical water jet was passed through the center of the spectrometer, and illuminated by sunlight admitted through a very narrow slit of the collimator. The angles of the different colors were accurately measured. Of course it was a difficult task to produce a jet exactly equal to that assumed in the calculations; hence, Doctor Pernter sometimes had to content himself with an approximate value. There was also some difficulty in bringing the water column to the exact center of the apparatus; this might have caused an error of not more than $\pm 4'$. Notwithstanding all these difficulties he succeeded in getting quite satisfactory data as regards the rainbows calculated for $a = 500\,\mu$ and $a = 250\,\mu$. We subjoin a table comparing the results of the calculations with those of the experiment. It is to be noted that in recording the colors seen in the experiment violet and rose were not distinguished; x stands for the color resulting from a mixture of hues.

With $a = 500\mu$, the colors succeeded each other as follows: pure red, orange, yellow, green, violet, blue, and the second violet; with $a = 250\mu$, red, orange, yellow, green, bluish green, blue, violet, rose. These data therefore afford the proof for Airy's assumption that the size of the raindrops plays an important part in the outcome of the phenomenon. As regards the secondary bows, another interesting observation was made. With $a = 500\mu$, twenty-four were numbered: the first eight consisted solely of violet (rose) and green or light blue; after the twelfth a band almost white, but shading somewhat into yellow, was seen, and the subsequent bows showed a trace of yellow before the violet; hence, the succession of hues was reversed. With $a = 250\mu$, eleven bows could be counted; the white band mixed with a tint of green occurred already in the fifth, and afterwards the hues followed each other again in reversed order. Comparing these results, we come to the conclusion that the number of visible bows decreases with the radius of the drops. The same was found true in the second rainbow; for with $a = 500\mu$, thirteen were observed; while with $a = 250\mu$, only five.

What we have said so far may suffice for the explanation of the rainbow as ordinarily observed and known to all. But perhaps we will not go amiss by considering more in particular also the white rainbow, a phenomenon of high importance for Airy's theory, because this explains it fully, while Descartes's view here leaves us in the dark.

A white rainbow may not infrequently be observed on mountains and on seashores, particularly in northern latitudes. If formed by sunlight, the principal bow is made up of a brilliant white, the margins are somewhat colored, the outer showing a yellowish and orange-red, the inner a bluish-violet tinge. The secondary bows, if any occur, are separated from the principal arch by a dark space, and their colors succeed one another in a reversed order, for a bluish seam lines the dark interval while the red lies toward the inside.

Since a white rainbow may be formed by sunlight as well as by moonlight, we are now to investigate the causes of the phenomenon. They may be reduced to three.

The first is the weak intensity of light in case of the lunar

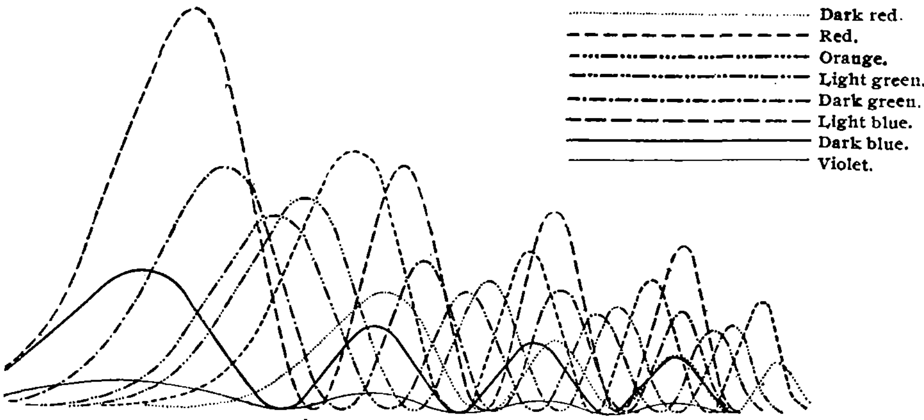

FIG. 4.—Showing how the bands of eight different colors overlap in case the radius of the drop measures 250μ. (Pernter.)

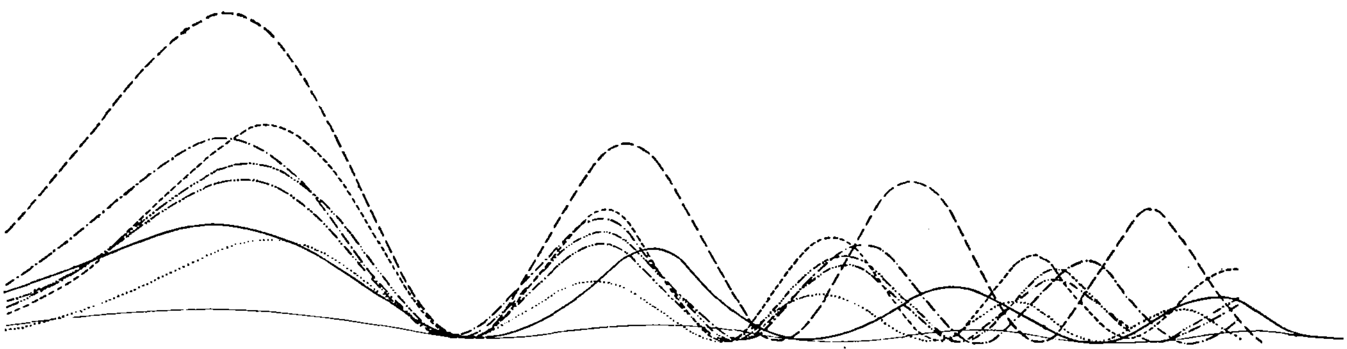

FIG. 5.—Showing how the bands of eight different colors overlap in case the radius of the drop measures 25μ. (Pernter.)

rainbow. Since it is a known fact,[2] that by lowering the intensity of a color beyond a certain limit, each color as such ceases to make its own impression and appears as a grayish white, we easily understand that on account of the weak intensity of moonlight the lunar rainbow shows a whitish appearance.

It would be very interesting to find out under what conditions of intensity the rainbow colors produce no effect on our visual organs. However, this question can not be answered with certainty. Messrs. Abney and Festing, it is true, have shown experimentally when color disappears from our sight, but these data can not be applied to the rainbow. First, there is no known standard to which we could refer the intensity of the rainbow colors. Moreover, since daylight, which is variable in brightness, mixes with the colors, the sensation itself will thus be differently affected. Finally, because the air as regards dryness and moisture, and the number of drops contained in a cubic meter (on which the intensity of colors depends) are variable, any estimate falls short of the reality.

A second cause is the inequality in size of the raindrops, whereby the different colors might be caused to overlap in such a way as to produce the sensation of white. Although we do not deny that this is possible, yet, since a white rainbow was never observed during a rainfall (it is assumed that it begins to rain when the drops have become at least 100μ in diameter) we need not dwell any longer on this explanation.

Very small drops are the third cause.

White occurs in every rainbow, whether in the principal or in a scondary one; however, we restrict the designation of "white rainbow" to those in which white is really prominent, without excluding differently colored shades.

Before we enter upon the explanation of this phenomenon, we must answer the question, in what case a mixture of colors gives rise to the sensation of white. Since every mixture of colors results into a pure spectral color and white, it is to be ascertained what percentage of each is required to make any color as such disappear. Mr. Abney proved that this percentage is the same for all colors, each disappearing in case a white light seventy-five times stronger be added. This means that white only then appears when the intensity of the color is 1.3 per cent of that of white. At first sight this law seems to import the impossibility of a truly white rainbow, since the calculated intensity of x is never as low as 1.3 per cent. The utmost we could expect is a sensible whitish shade in case x reaches 4 per cent. and below. Hence, in our explanation we have to show that x reaches the limit stated by Mr. Abney.

We must bear in mind that Mr. Abney made his experiments in a dark room, while the rainbow is formed in full daylight and sunshine; whence it follows that since the sunlight is white and intense in comparison with the colors of the rainbow, the percentage of x is lessened while that of white is increased. If, therefore, the intensity of x be near the limit, 1.3 per cent, and if daylight be added, we understand that a truly white rainbow can be the outcome.

A series of interesting experiments, carried out by Professor Pernter, confirms this explanation.

By means of ordinary atomizers he produced a fine water-spray (the size of the drops could not be measured on account of the small quantity of water), sunlight was allowed to fall upon it, and the phenomenon observed comported well with the raindrops figured out for very small drops. Red was wanting in the principal rainbow, and the orange showed a distinctly yellowish tint. Then very whitish shades of green and blue were seen, after which the violet came out more clearly as such. In full daylight these colors certainly would have given the rainbow represented in No. I of fig. 3; this conclusion is corroborated by the large extension of the principal rainbow.

In another experiment the water spray was dense enough to find the exact size of the drops. They measured 5.3 in radius. When sunlight fell upon the cloud of water dust a splendid white rainbow was obtained, owing, without doubt, to the

[2] Cfr. Abney and Festing, "Color Photometry," Part III, Philosoph. Transact., London, vol. 183 (1892), p. 537.

white sunlight, which, although admitted in small quantity, increased the percentage of white enough to reach the limit for x. With $a = 8{:}4\ \mu$ a white rainbow was yet obtained, the white band, however, had already decreased in width.

RADIATION IN THE SOLAR SYSTEM.

By Prof. J. H. POYNTING, F. R. S.

[Afternoon address delivered at the Cambridge meeting of the British Association for the Advancement of Sciences, August 23, 1904. Reprinted from Nature, September 22, 1904, vol. 70, p. 512.][1]

I propose to discuss this afternoon certain effects of the energy which is continuously pouring out from the sun on all sides with the speed of light—the energy which we call sunlight when we enjoy the brilliance of a cloudless sky, which we call heat when we bask in its warmth, the stream of radiation which supports all life on our globe and is the source of all our energy.

As we all know, this ceaseless stream of energy is a form of wave motion. If we pass a beam of sunlight, or its equivalent, the beam from an electric arc, through a prism, the disturbance is analyzed into a spectrum of colors, each color of a different wave length, the length of wave changing as we go down the spectrum from, say, 1/30,000 of an inch in the red to 1/80,000 of an inch in the blue or violet.

But this visible spectrum is merely the part of the stream of radiation which affects the eye. Beyond the violet are the still shorter waves, which affect a photographic plate or a fluorescent screen, and will pass through certain substances opaque to ordinary light. Here, for instance, is a filter, devised by Professor Wood, which stops visible rays, but allows the shorter invisible waves to pass and excite the fluorescence of a platinocyanide screen.

Again, beyond the red end are still longer waves, which are present in very considerable amount, and can be rendered evident by their heating effect. We can easily filter out the visible rays and still leave these long waves in the beam by passing it through a thin sheet of vulcanite. A piece of phosphorus placed at the focus of these invisible rays is at once fired, or a thermometer quickly rises in temperature. The waves which have been observed and studied up to the present time range over some nine octaves, from the long waves described to the section yesterday by Professor Rubens, waves of which there are only 400 in an inch, down to the short waves found by Schumann in the radiation given off by hydrogen under the influence of the electric discharge, waves of which there are a quarter of a million in an inch. No doubt the range will be extended.

Radiant energy consists of a mixture of any or all of these wave lengths, but the eye is only sensitive at the most to a little more than one octave in the nine or more.

This radiation is emitted not only by incandescent bodies such as the sun, the electric arc, or flames. All bodies are pouring out radiant energy, however hot or cold they may be. In this room we see things by the radiation which they reflect from the daylight. But besides this borrowed radiation, every surface in the room is sending out radiation of its own. Energy is pouring forth from walls, ceiling, floor, rushing about with the speed of light, striking against the opposite surfaces, and being reflected, scattered, and absorbed. And though this radiation does not affect our eyes, it is of the utmost importance in keeping us warm. Could it be stopped, we should soon be driven out by the intense cold, or remain to be frozen to death.

As the temperature of a body is raised, the stream of radiation it pours out increases in quantity. But it also changes in quality. Probably the surface always sends out waves of all lengths from the longest to the shortest, but at first when it is cold the long waves alone are appreciable. As it gets hotter, though all the waves become more intense, the shorter ones increase most in intensity, and ultimately they become so prominent that they affect our sense of sight, and then we say that the body is red or white hot.

The quality of the stream depends on the nature of the surface, some surfaces sending out more than others at the same temperature. But the stream is the greatest from a surface which is, when cold, quite black. Its blackness means that it entirely absorbs whatever radiation falls upon it, and such a surface, when heated, sends out radiation of every kind, and for a given temperature each kind of radiation is present to the full extent; that is, no surface sends out more of a given wave length than a black surface at a given temperature.

A very simple experiment shows that a black surface is a better radiator, or pours out more energy when hot, than a surface which does not absorb fully, but reflects much of the radiation which falls upon it. If a platinum foil with some black marks on it be heated to redness, the marks, black when cold, are much brighter than the surrounding metal when hot; they are, in fact, pouring out much more visible radiation than the metal.

It is with these black surfaces that I am concerned to-day. But, inasmuch as it seems absurd to call them black when they are white hot, I prefer to call them full radiators, since they radiate more fully than any others.

For a long time past experiments have been made to seek a law connecting the radiation or energy flow from a black or fully radiating surface with its temperature. But it was only 25 years ago that a law was suggested by Stefan which agrees at all satisfactorily with experiment. This law is that the stream of energy is proportional to the fourth power of the temperature, reckoned from the absolute zero, 273° below freezing point on the centigrade scale. This suggestion of Stefan served as the starting point of new and most fertile researches, both theoretical and practical, and we are glad to welcome to this meeting Professors Wien, Lummer, and Rubens, who have all done most brilliant work on the subject.

Among the researches on radiation recently carried out is one by Kurlbaum, in which he determined the actual amount of energy issuing from the black or fully radiating surface per second at 100° C., and, therefore, at any temperature.[2]

Here is a table which gives the amount at various temperatures, as determined by Kurlbaum:

Rate of flow of energy from one square centimeter of fully radiating or "black" surface.

Absolute temperature.	Calories (grams of water heated 1°) per second.
0°	0.0
100°. Air boils	0.000127
300°. Earth's surface	0.0103
1,000°. Red heat	1.27
3,000°. Arc carbon	103
6,000°	1,650
6,250°	1,930

As an illustration of the "fourth power law," let us see what value it will give us for the temperature of the sun, assuming that he is a full radiator, or that his surface, if cooled down, would be quite black.

We can measure approximately the stream of energy which the sun is pouring out by intercepting the beam falling on a

[1] The foot notes to this article, where not otherwise credited, are adapted from a technical paper by Professor Poynting: "Radiation in the solar system: its effect on temperature and its pressure on small bodies." Philosophical Transactions of the Royal Society, Series A, 1903, vol 202, p. 525.—*F. O. S.*

[2] [The constant factor, the product of which by the fourth power of the absolute temperature gives the amount of radiant energy per square centimeter per second, is called the constant of radiation. According to Kurlbaum, this constant, expressed in units of mechanical energy, is 5.32×10^{-5} ergs. By dividing this by the mechanical equivalent of heat, it becomes 1.27×10^{-12} calories or thermal units.]